The Safest Path: Analyzing the Effects of Crash Costs on Route Choice and Accessibility

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ABSTRACT

The "safest path" is proposed to optimize the on-road safety of individuals and minimize the cost of crashes. In this study, the framework of a link-based crash cost analysis is built and applied to assess the crash cost of each link segment on the road network of the Minneapolis - St. Paul area based on Safety Performance Functions from the perspective of travelers. The safest path is then found for all OD pairs to compare flow patterns and accessibility distributions with those based on the traditional shortest travel time path. While, the safest path does not coincide with the shortest path, the accessibility distributions have similar patterns.

INTRODUCTION

Traffic crashes were a very early byproduct of the automobiles, and remain a serious issue globally (1, 2). There were more than 5,000,000 police-reported motor vehicle crashes every year from 2005 to 2014 in the United States (3), including over 30,000 traffic fatalities annually. Moreover, the total number of crashes increased from 2011 to 2014, when 13 states saw a more than 5% fatality increases from 2013 to 2014 (4).

Individual route choices allow travelers to avoid using more dangerous roads, or roads with other dangerous drivers; however, few, if any, travelers know these risks.

The concept of 'Sustainably Safe Traffic' was proposed in the Netherlands, which encourages travelers to use safe roads as much as possible to reduce road crash casualties (5). The safest path, which is the optimal solution of route choices from the perspective of safety, could optimize on-road safety for individuals and minimize the economic cost of crashes.

Based on a crash risk estimation model, Lord (6) estimated the crash risks of a sample network and found the safest paths for individual vehicles that a driver would have the lowest probability of being involved in a crash. The method shows the potential of searching the safest path for the OD pairs on the actual road network.

However, the consequence or the cost of crashes varies based on the severities, from fatal crashes to property damage only crashes. Monetizing crash consequences is widely used to weight the severities. Hence, we define the safest path as the route with the lowest total crash cost, subject to travelers engaging in the same set of activities at the same locations.

Crash costs cover various components, including direct cost (such as property damage, medical cost, and legal costs), indirect cost (such as productivity loss for work and family, and tax losses), and intangible cost (such as the loss of life or degradation in quality of life and the pain and suffering for both victims and their families) (7, 8). Notably, the loss of life is the most economically expensive elements. For instance, Trottenberg and Rivkin (9) indicates an economic Value of a Statistical Life (VSL) of $9.4 million in 2015. Besides, VSL has been widely used to measure the crash costs for different injury severities. VSL is used as a baseline to monetize the consequences of various crash severities relative to loss of life and thus express the unit value of a crash (10).

Hence, this study first builds a framework for link-based crash cost analysis, and, from the perspective of travelers, assesses the crash cost for each link segment on the network for the Minneapolis - St. Paul (Twin Cities) area based on Safety Performance Functions (SPFs). This paper estimates the expected crash cost borne by travelers themselves along various travel routes.

Moreover, this paper finds the safest path for all OD pairs in the Twin Cities region, based on which we estimate the work trip flow on each link segment. The safest paths were then aggregated into an accessibility matrix, and compared with the traditional travel time based accessibility. The accessibility loss of using the safest path was analyzed considering the time restriction, which indicates the penalties of pursuing a minimum crash cost expressed by accessibility. Similarly, we measured the accessibility loss of using the shortest travel time path considering the crash cost restriction.

The data, methodology, SPF models, results and conclusion of this study are shown in sections 3 - 7 in turn.

DATA

Several sources of data are applied into this study.

- **Crash data from Minnesota**

  Crash data from Minnesota were acquired by the research team from Minnesota Department of Transportation. The data includes crash records from 2003 to 2014 specific to different types of crashes. Based on the data, the number of crashes by severities is shown in Table 1, along with costs per crash used by MnDOT and our estimate of statewide annual cost (a 12 year average).

TABLE 1 : The Number of Crashes by Severity and Economic Impact

Severity	Number of Crashes (12 y)	Cost per Crash	Statewide Annual Cost
Fatal Crashes	1,472	$10,600,000	$1,300,266,666
Type A Crashes	6,698	$570,000	$318,155,000
Type B Crashes	40,125	$170,000	$568,437,500
Type C Crashes	108,450	$83,000	$750,112,500
Type N Crashes	372,670	$7,600	$236,024,333
Total	529,415		$3,172,996,000

[1] Type A crashes: incapacitating injury crashes; Type B crashes: non-incapacitating injury crashes; Type C crashes: possible injury crashes; Type N crashes: property damage-only crashes (11).

  For each year, the crash data contains the crash level data, including date of crashes, GIS attributes, type of crashes, severity, and other related information, such as weather, light, road characteristics, and geometric design. The data displays crash records as a shapefile based on GIS attributes, such as route number, reference points, and coordinates. In this study, only crashes in the seven county Twin Cities region were selected, and the number of crashes for each link is aggregated by crash severity.

- **Speed and Road Network Data**

  Speed data was acquired by the research team from the Metropolitan Council of the Twin Cities. The data was originally collected by millions of GPS logging and navigation devices and organized by TomTom, and then aggregated and processed based on link segments of roadway network (12). These speed data were organized by road classification, time period, and speed percentiles. For 8 Functional Roadway Classifications (FRCs), speed data were separated into 4 groups, in which FRC0 to FRC4 were grouped into one dataset. For different time periods, considering the traffic properties, the time of a day was divided into seven parts, including Overnight, Morning Peak Hours (Two parts), Mid-Day, Evening Peak Hours (Two Parts) and Evening. Moreover, for each group, different percentiles of speed measurements, from 5th to 95th percentile, in the same time period of a day were joined in the same datasets. The 5th percentile speed shows the speed on links in the times which were the fastest 5 percent of those recorded, while the 95th percentile speeds similarly stands for the slowest speed.

  All the accessibility and traffic routing this study used the 50th percentile speed. Speed variance uses 10th and 90th percentiles.

  The Twin Cities region has 48,009 links according to the TomTom road network.

- **2010 Transportation Analysis Zone (TAZ) System**

  2010 Transportation Analysis Zone system in Twin Cities was developed by the Metropolitan Council. This data is displayed as a polygon shapefile that shows the 2010 TAZs boundaries, employment, and household data for each TAZ (13). For measuring job accessibility, the features in the region were selected, and the centroid of each TAZ was extracted to be used as the origin and destination.

- **AADT**

  An estimate of daily traffic (AADT) was collected from MnDOT, which is shown as a GIS Shapefile. The features were selected and joined to the road network.

- **Federal Urban/Rural GIS Shapefile**

  Federal Urban/Rural GIS Shapefile was acquired from Transportation Data and Analysis, MnDOT (14) and defined by Federal Adjusted Urban Area boundaries. The data covers the roadways of Minnesota, which are divided into Urban Roads, Small Urban Roads, and Rural Roads. The data were selected and joined with the road network.

- **LEHD Origin-Destination Employment Statistics dataset (LODES7.0)**

  The LEHD Origin-Destination Employment Statistics dataset (LODES 7.0), where LEHD itself stands for Longitudinal Employment Household Dynamics, is used to measure the work trip flow based on both the safest path and the shortest travel time path depending on the definition of betweenness. The data was obtained from the United States Census Bureau (15), and its Origin-Destination (OD) table was used to track the actual OD pairs of workers in Twin Cities at the census block level.

  To join the OD table to the GIS map, the Census's TIGER/Line shapefile at the block level of Minnesota in 2010 was used (16). The centroid of each block is extracted as the origin and destination for actual trips. These were aggregated to TAZs

METHODOLOGY

Safety Performance Functions

Safety Performance Functions (SPFs) are defined by Highway Safety Manual (HSM) (17) as statistical base models to measure the average crash frequency with specified base conditions. SPFs not only can estimate the crash frequency with the existing roadway conditions, but can predict it by applying the future conditions with a projected AADT (18).

The conventional variables for SPFs in HSM are AADT and segment length in the case of roadway segments. But additional variables can be added if those variables contribute to estimate crash frequencies.

The HSM suggests using the Negative Binomial Distribution to estimate SPFs, this extends the Poisson distribution, but better models the crash data due to overdispersion, data with a higher variance than its mean. The Negative Binomial model of SPFs could be expressed as (18):

$$log(N) = \beta_0 + \sum_{k=1}^{p} \beta_k x_k \tag{1}$$

Where:
N stands for number of crashes,
x_k stands for independent variables,
p stands for the number of independent variables,
β_k are coefficients.

Crash Cost Estimation

MnDOT estimates the standard crash values, which refers to the average cost of all fatalities/injuries/damages per crash, by severities based on value of single life recommended by the USDOT and other costs related to crashes (19). The suggested MnDOT crash values are shown in Table 1. Hence, the crash cost per vehicle kilometer traveled for a specific link could be expressed as the following functions,

$$C_{S,i} = \sum_q R_{S_q,i} * L_i * u_{S_q} \tag{2}$$

$$R_{S_q,i} = \frac{N_{i,q}}{12 * 365 * AADT * L_i} \tag{3}$$

Where:
$C_{S,i}$ stands for the expected crash costs on link i,
$R_{S_q,i}$ stands for average number of type q crash per vehicle kilometer traveled on link i,
L_i stands for the segment length of link i,
u_{S_q} stands for the unit crash value per type q crash,
$N_{i,q}$ stands for the average number of type q crash on link i.

The Safest Path

The safest path is proposed as a new rule of traffic route assignment to minimize the crash cost. It is defined as the route with the lowest crash cost between a given OD pair, which is expressed as

$$C_{S,P_{OD,k}} = \sum_{i \in P_{OD,k}} C_{S,i} \tag{4}$$

$$C_{S,P_{OD}} = min(C_{S,P_{OD,k}}) \tag{5}$$

Where:
$P_{OD,k}$ refers to the k^{th} path between origin O and destination D,
$C_{S,P_{OD,k}}$ is the crash cost of the k^{th} path between origin O and destination D,
$C_{S,P_{OD}}$ stands for the minimum cumulative crash cost between O and D, where the P_{OD} refers to the safest path

Betweenness

Betweenness is defined by Freeman (20), which quantifies the times of a link on the road network that is passed by the shortest paths between OD pairs, which is written as,

$$B_i = \frac{q_i}{Q} \tag{6}$$

Where:

B_i stands for the betweenness of link segment i,

q_i stands for the number of trips passing through i by using a given paths. In this case, the path refers to either the safest path $q_{S,i}$ or the shortest travel time path $q_{T,i}$.

Q stands for the total number of trips.

Based on the OD table of LODES data, the total number of work trips is fixed for both the safest path and the shortest travel time path. Hence, we concern more about the differences of q_i by using the safest path compared with the shortest one.

Accessibility Measure

The Cumulative Opportunity Measure (21, 22) is the most basic method to calculate accessibility. It counts the number of opportunities (valued destinations, here, jobs) within a given threshold using a certain traffic mode.

$$A_O = \sum_D O_D f(C_{OD}) \tag{7}$$

$$f(C_{OD}) = \begin{cases} 1 & if\ C_{OD} \leq W \\ 0 & if\ C_{OD} > W \end{cases} \tag{8}$$

Where:

A_O stands for the job accessibility of origin O,

O_D stands for the number of jobs in destination D,

C_{OD} stands for the travel costs between origin O and destination D. From the perspective of crash cost, C_{OD} refers to the minimum crash cost ($C_{S,OD}$). While from the perspective of time cost, it refers to the time cost ($C_{T,OD}$) ,

W represents the thresholds, which could be both the crash cost threshold (W_S) or the travel time threshold (W_T) .

Based on accessibility measurement, accessibility difference was proposed to express the loss of pursing the optimal path from one aspect rather than another in terms of the reduction of reachable destinations. For instance, the accessibility difference of using the shortest travel time path from the perspective of crash cost (A_{C_T,O,W_S}) is measured as,

$$A_{C_T,O,W_S} = A_{O,S,W_S} - A_{O,T,W_S} \tag{9}$$

Where:

A_{O,S,W_S} stands the accessibility of origin O based on the safest path within an crash cost threshold of W_S;

A_{O,T,W_S} stands for that of using the shortest path within the same crash cost threshold.

Based on the Cumulative Opportunity Measure, the process of accessibility assessment is divided into two parts.

The first part was to search the safest path and the shortest travel time path. The cumulative crash cost and travel time were computed for both the safest path and the shortest travel time path.

The second part was to join the job opportunity of destinations with the matrices of travel cost, and calculate the accessibility for each origin by comparing the travel cost with the predetermined cost threshold. We used SQL Sever to calculate this part.

Accessibility difference is then computed.

SPF MODELS

On the basis of the conventional variables for SPFs, we tested 4 new models of SPFs by adding in new variables depending on the available data.

- **Model 1**

  The conventional SPF was tested as Model 1 in our study only including the independent variables of AADT (V) and segment length (L). Transforming AADT and L into natural log form:

$$N = V^{\beta_1} * L^{\beta_2} exp(\beta_0) \tag{10}$$

- **Model 2**

  Model 2 added speed (S), extending Model 1:

$$N = V^{\beta_1} * L^{\beta_2} exp(\beta_0 + \beta_3 S) \tag{11}$$

- **Model 3**

  Model 3 then added another variable, speed variance (S_{Var}), which was defined as the speed differences of the 10th and 90th percentile speed from the speed data:

$$N = V^{\beta_1} * L^{\beta_2} exp(\beta_0 + \beta_3 S + \beta_4 S_{Var}) \tag{12}$$

- **Model 4**

  Model 4 added a dummy variable (U), Urban, based on Model 3, which represents whether the link segment is an urban road or not (many parts of the seven county region are still rural or exurban, rather than urban or suburban):

$$N = V^{\beta_1} * L^{\beta_2} exp(\beta_0 + \beta_3 S + \beta_4 S_{Var} + \beta_5 U) \tag{13}$$

The results of the 4 SPF models are shown in Table 2.

From Table 2, for different type of crashes, from fatal crashes to property damage only crashes, the conventional variables, AADT and segment length, show positive effects on crash counts in all models as expected. It recognizes that links with larger AADT or longer length tend to have more crashes of any severities, which is reasonable and easily understood.

Other variables, speed, speed variance and urban, also affect crash count positively for all crash severities. Driving with a higher speed is more likely to result in crashes than with lower speed, which is consistent with common sense and understanding of human reaction times. Speed variance, which may reflect the level of shockwaves, is expected to have positive effects on crash frequency. Moreover, urban roads tend to have more crashes than small urban and rural roads based on the regression results. It is consistent with Department of Public Safety (23).

Comparing the different models, Model 4 is preferred, as it has a lower AIC and a higher pseudo R^2. Basically, all the added variables are positive and statistically significant for crash counts. Hence, Model 4 was selected to applied into the crash frequency estimation for the link-based crash cost analysis.

TABLE 2 : Regression Results of SPF Models

		Model 1			Model 2			Model 3			Model 4		
		Coef.	SE	Signif.	Coef.	SE	Signif.	Coef.	SE	Signif.	Coef.	SE	Signif.
Fatal	Intercept	-6.5139	0.2965	***	-7.0936	0.2974	***	-7.2130	0.2966	***	-7.2883	0.2991	***
	V	0.2979	0.0334	***	0.2303	0.0336	***	0.2081	0.0338	***	0.1735	0.0356	***
	L	0.9560	0.0551	***	0.8006	0.0579	***	0.8093	0.0580	***	0.8569	0.0606	***
	S				0.0173	0.0025	***	0.0171	0.0026	***	0.0183	0.0026	***
	S_{Var}							0.0125	0.0031	***	0.0120	0.0031	***
	U										0.4272	0.1362	**
	AIC	4785			4724.7			4733.2			4724.7		
	pseudo R^2	0.0788			0.0916			0.08952			0.09155		
Type A	Intercept	-5.5743	0.1498	***	-5.4902	0.1587	***	-5.5697	0.1591	***	-5.9522	0.1666	***
	V	0.3507	0.0167	***	0.3566	0.0173	***	0.3420	0.0174	***	0.2916	0.0181	***
	L	0.5086	0.0250	***	0.5248	0.0267	***	0.5273	0.0268	***	0.5768	0.0277	***
	S				-0.0021	0.0014		-0.0022	0.0013		0.0002	0.0014	
	S_{Var}							0.0083	0.0017	***	0.0081	0.0017	***
	U										0.8495	0.0802	***
	AIC	17682			17538			17663			17538		
	pseudo R^2	0.0457			0.0538			0.04691			0.05377		
Type B	Intercept	-5.1561	0.0929	***	-5.1985	0.0996	***	-5.3350	0.1000	***	-5.8125	0.1040	***
	V	0.5106	0.0106	***	0.5087	0.0107	***	0.4834	0.0108	***	0.4249	0.0109	***
	L	0.4663	0.0145	***	0.4595	0.0153	***	0.4723	0.0153	***	0.5305	0.0157	***
	S				0.0009	0.0008		0.0004	0.0008		0.0029	0.0008	***
	S_{Var}							0.0155	0.0012	***	0.0150	0.0011	***
	U										1.0405	0.0457	***
	AIC	58397			57734			58246			57734		
	pseudo R^2	0.0535			0.0643			0.05599			0.06432		
Type C	Intercept	-4.8030	0.0817	***	-5.0000	0.0892	***	-5.2581	0.0895	***	-5.9340	0.0925	***
	V	0.5865	0.0094	***	0.5843	0.0095	***	0.5558	0.0095	***	0.4947	0.0096	***
	L	0.4265	0.0125	***	0.4036	0.0130	***	0.4339	0.0130	***	0.4952	0.0133	***
	S				0.0034	0.0008	***	0.0019	0.0008	*	0.0046	0.0008	***
	S_{Var}							0.0237	0.0011	***	0.0224	0.0011	***
	U										1.2951	0.0389	***
	AIC	97095			95632			96636			95632		
	pseudo R^2	0.0474			0.0618			0.05193			0.0618		
Type N	Intercept	-3.5823	0.0694	***	-3.9421	0.0771	***	-4.1860	0.0773	***	-4.9617	0.0786	***
	V	0.5794	0.0081	***	0.5808	0.0081	***	0.5541	0.0081	***	0.4999	0.0082	***
	L	0.4059	0.0106	***	0.3701	0.0110	***	0.4114	0.0110	***	0.4721	0.0111	***
	S				0.0054	0.0007	***	0.0032	0.0007	***	0.0058	0.0007	***
	S_{Var}							0.0246	0.0010	***	0.0226	0.0010	***
	U										1.3603	0.0316	***
	AIC	159173			156904			158448			156904		
	pseudo R^2	0.0388			0.0525			0.04319			0.05252		

RESULTS

Crash Cost Assessment

Crash costs on link segments range between \$0.00-0.05, in which more than 78% of link segments have a crash cost lower than \$0.01. But there are exceptions, 3% of link segments have a crash cost greater than \$0.05, and the maximum crash cost is around \$5 on links with a higher crash count but a low AADT. The mean value of crash cost of the link segments in Twin Cities area is \$0.01.

Figure 1 displays the patterns of the assessment results for the link-based crash cost analysis.

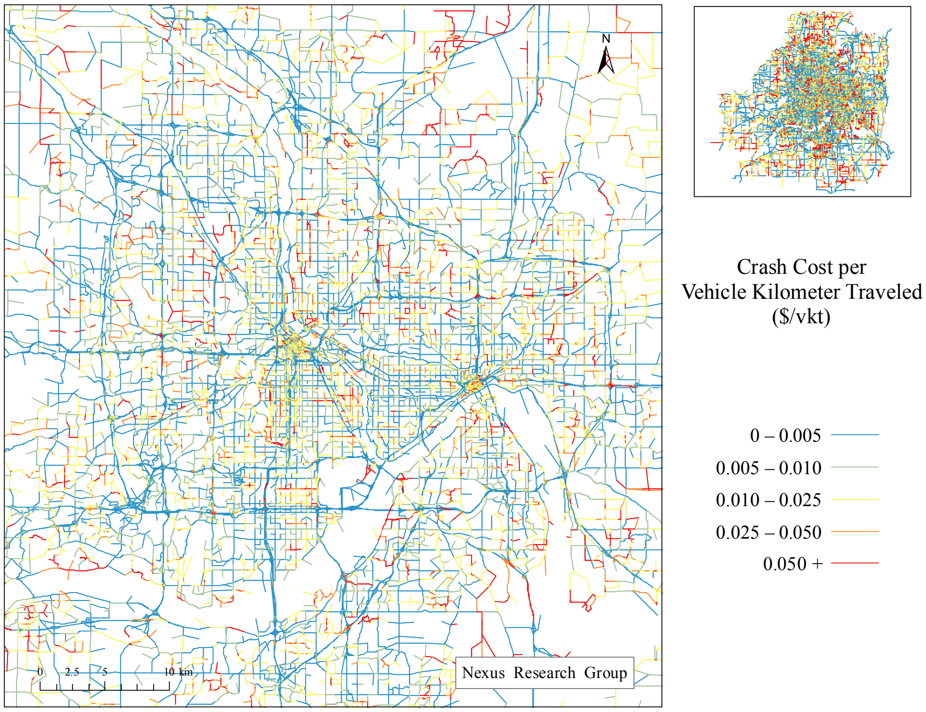


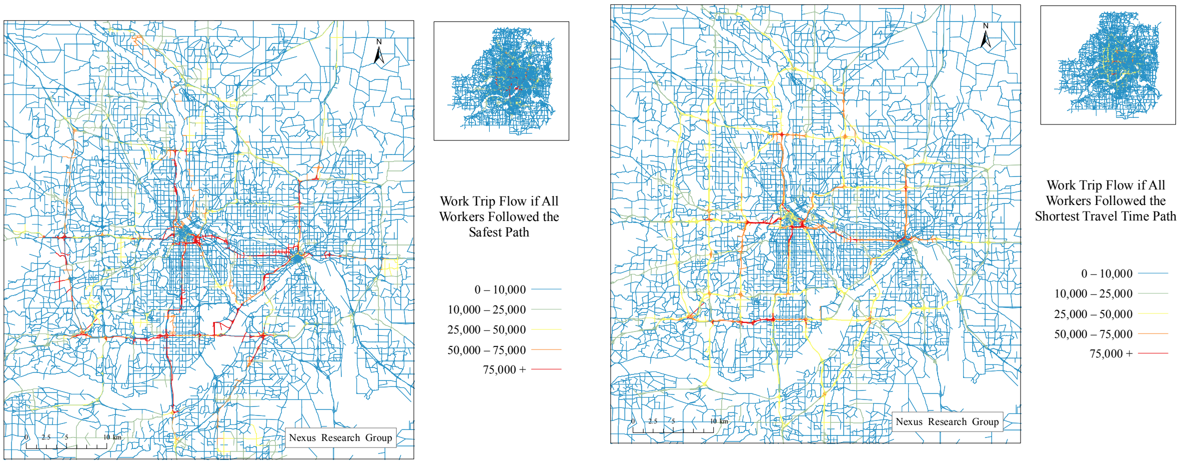
FIGURE 1 : Link-based Crash Cost Estimation

From Figure 1, the shape of the highway network emerges clearly on the map of Twin Cities roads. The highway link segments are more likely to appear blue, which implies a lower crash cost per vehicle-km than local roads. Such a pattern is expected since it has been generally found that freeways are safer than local roads (24, 25).

Work Trip Flow Estimation

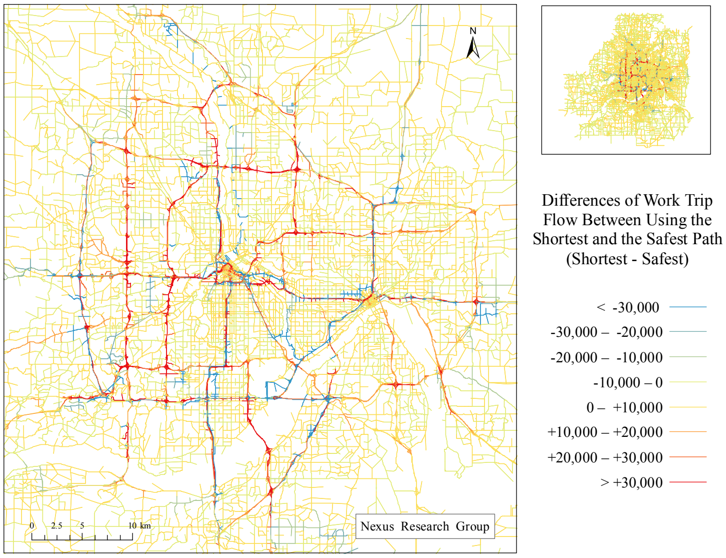
The flow of work trips based on the safest path is shown in Figure 2a

Using the safest path, highways have relative higher work trip flows. It is thought reasonable since, at first, highways are designed to have higher capacity and serve more vehicles, and, at second, the crash cost on the highway link segments are lower. Figure 2b shows the estimated flow based on the traditional shortest travel time path. Comparing with Figure 2a, Figure 2b displays that the work trip flows on the highway link segments are still higher than the local roads, but the trips are more evenly distributed on the highway network.



(a) Work Trip Flow Based on the Safest Path

(b) Work Trip Flow Based on the Shortest Travel Time Path



(c) Differences of Work Trip Flow between Using the Safest Path and the Shortest Travel Time Path

FIGURE 2 : Work Trip Flow Estimates

The differences of work trip flows between using the safest paths and the shortest travel time path are shown more clearly in Figure 2c, in which red lines refer to significant higher trip counts of using the shortest travel time path, while blue lines refer to significant higher trip counts of using the safest path.

Accessibility Measurement

Figure 3 shows the job accessibility based on the safest path, with the crash cost threshold changing from \$0.10 to \$0.30.

The basic distribution pattern of job accessibility is that TAZs in or around downtown Minneapolis have a higher job accessibility, which are visualized in red. The accessibility decreases gradually from the downtown to exurban areas shown by the color changes from red to light blue. It is reasonable to have such a pattern in the Twin Cities region since job opportunities are centered on downtown Minneapolis, which means residents living in or around downtown need less time to reach the same number of job opportunities, and have a lower crash rate along the home-to-work trips.

From Figure 3a to 3f, job accessibility increases significantly overall with a higher level of crash cost threshold. Within the \$0.30 crash cost, most residents in the Twin Cities region can reach most job opportunities by using the safest path. The effects of crash cost threshold on job accessibility reflect the trade-off between willingness-to-pay for crash cost and reachable job opportunities.

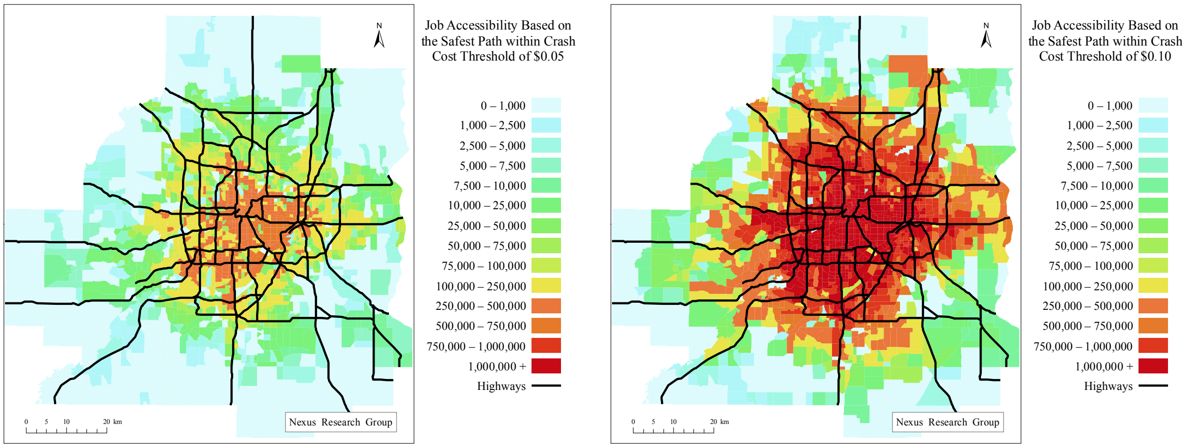
Comparing with Figure 4, which shows the job accessibility based on the shortest travel time path, the changes of job accessibility based on the safest path show strong discontinuities between adjacent TAZs. A TAZ with a lower job accessibility could directly neighbor a TAZ with higher accessibility. This is due to a higher crash cost for some link segments that traffic from some TAZs needs to pass through. We can think of these as *safety bottlenecks*.

Accessibility Difference Analysis

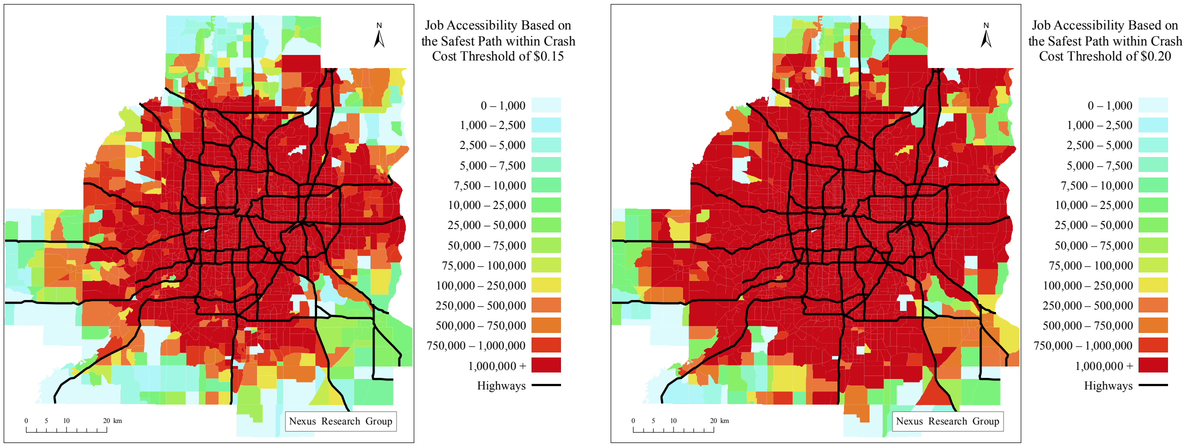
Figure 5 shows the difference in accessibility of using the safest vs. the shortest path in terms of jobs that can be reached. More jobs can be reached in a given time threshold on the shortest path than the safest path. From Figure 5a to 5f, accessibility differences increase along with a higher time threshold as a whole, which is visualized as extensions of green color area on the maps. However, accessibility differences in the downtown area starts to decline when the time threshold is larger than 40min (Figure 5d - 5f). It indicates that living in the downtown area can reach most of the job opportunities with a time threshold greater than 40min no matter whether the safest or the shortest travel time path is selected.

Similarly, Figure 6 shows the accessibility difference of using the shortest travel time path compared with the safest path within the crash cost threshold from \$0.10 to \$0.30, which implies the accessibility loss of using the shortest travel time path considering the safety cost.

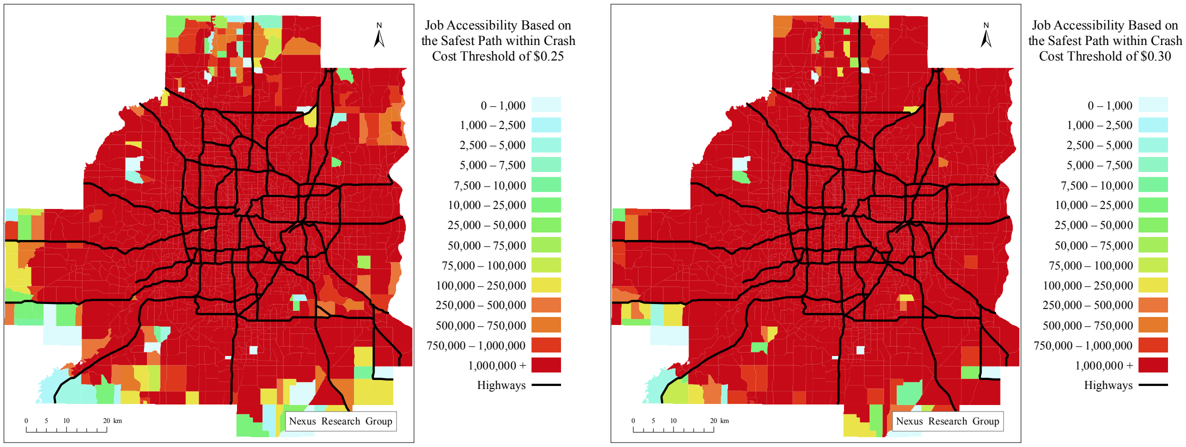
As with Figure 5, a higher accessibility loss is centered on the downtown area, at first, with a smaller crash cost threshold, \$0.10. Accessibility loss increases overall with an increased crash cost threshold. However, in the downtown area, the accessibility loss starts to decrease when the threshold is higher than \$0.20.



(a) $0.05 (b) $0.10

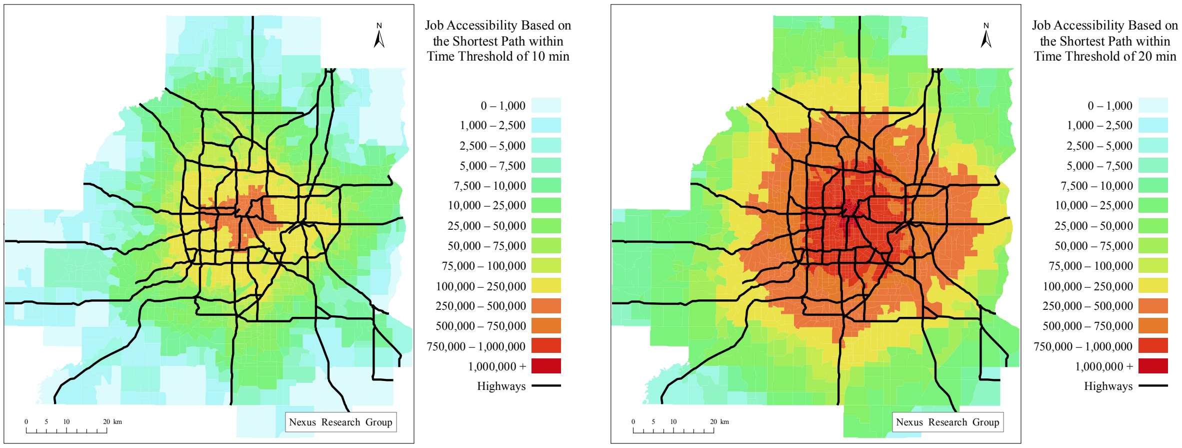


(c) $0.15 (d) $0.20



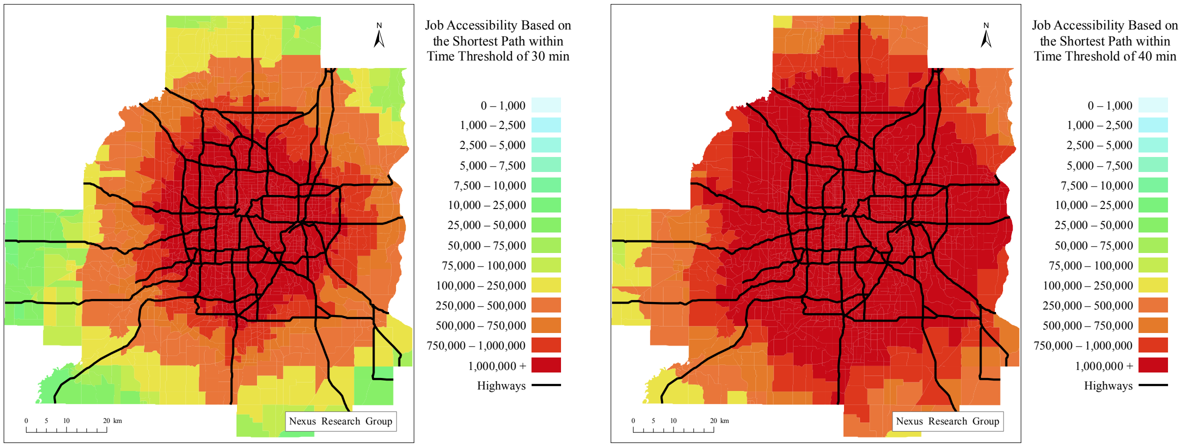
(e) $0.25 (f) $0.30

FIGURE 3 : The Job Accessibility Based on the Safest Path with Different Crash Cost Thresholds from $0.10 to $0.30



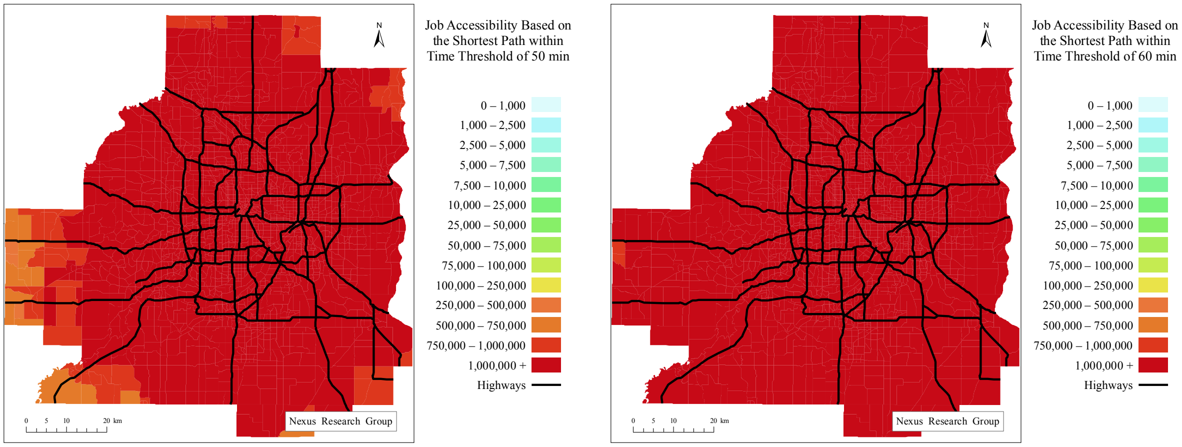
(a) 10 minutes

(b) 20 minutes



(c) 30 minutes

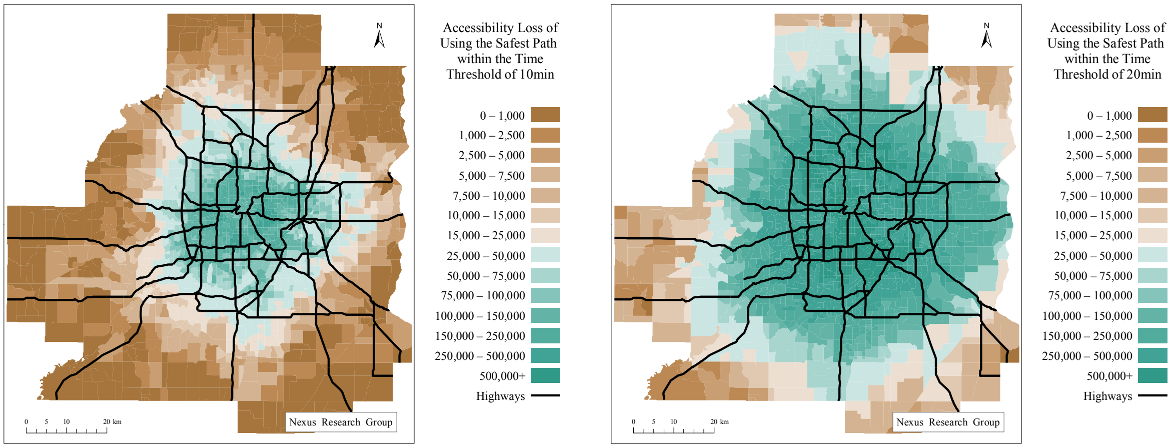
(d) 40 minutes



(e) 50 minutes

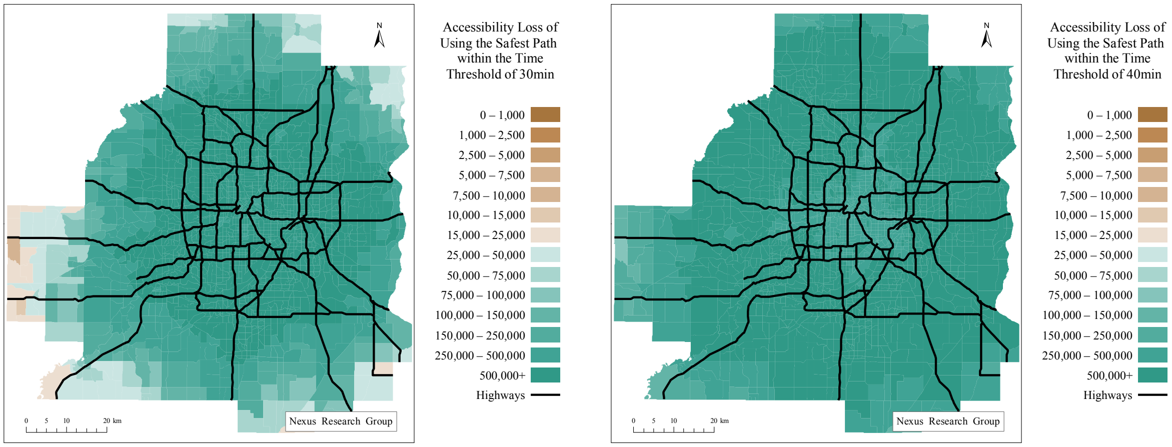
(f) 60 minutes

FIGURE 4 : The Job Accessibility Based on the Shortest Travel Time Path with Different Time Thresholds from 10 Minutes to 60 Minutes



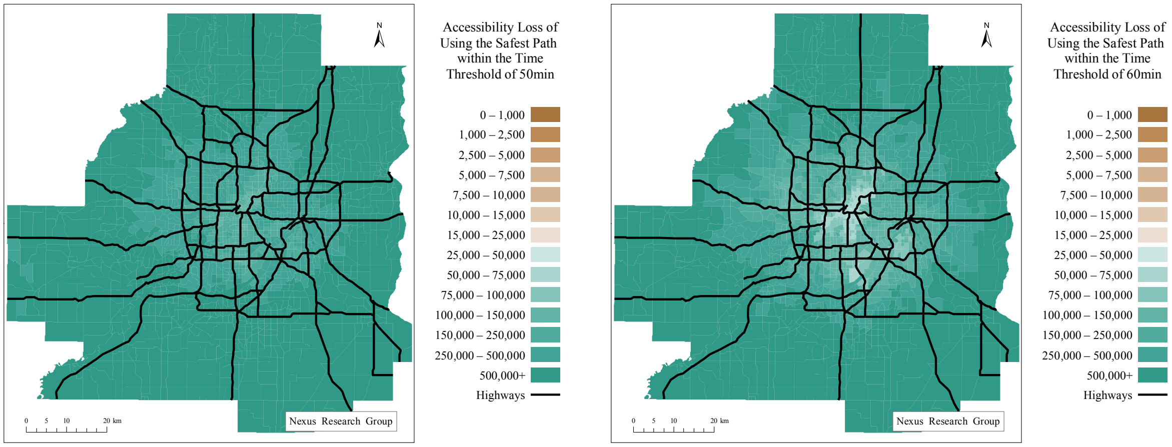
(a) 10 Minutes

(b) 20 Minutes



(c) 30 Minutes

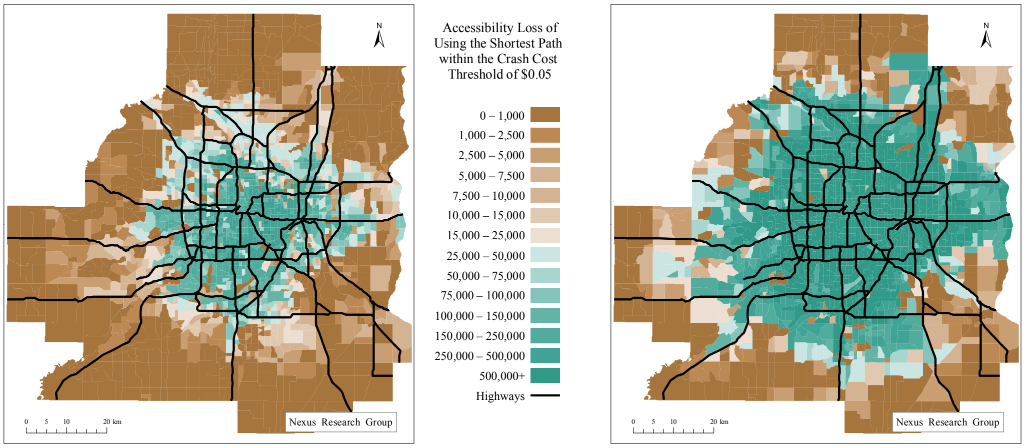
(d) 40 Minutes



(e) 50 Minutes

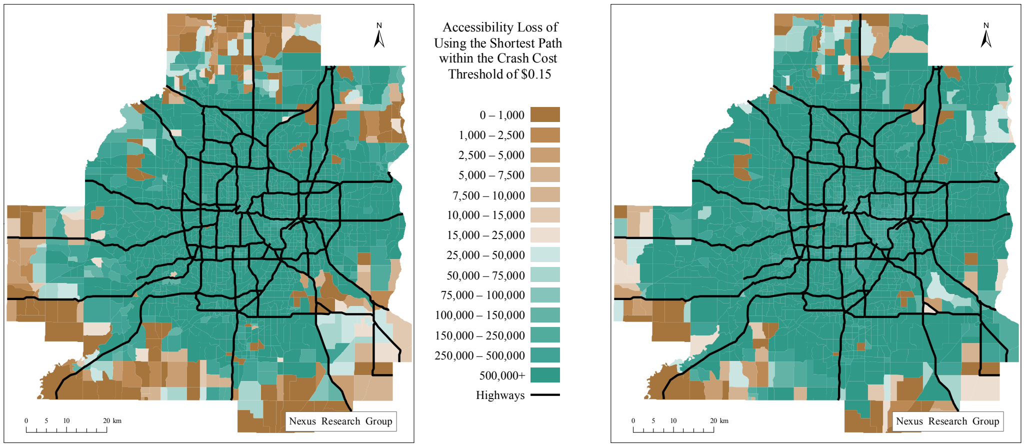
(f) 60 Minutes

FIGURE 5 : Accessibility Loss of Using the Safest Path Comparing with the Shortest Travel Time Path with different Time Threshold from 10min to 60min



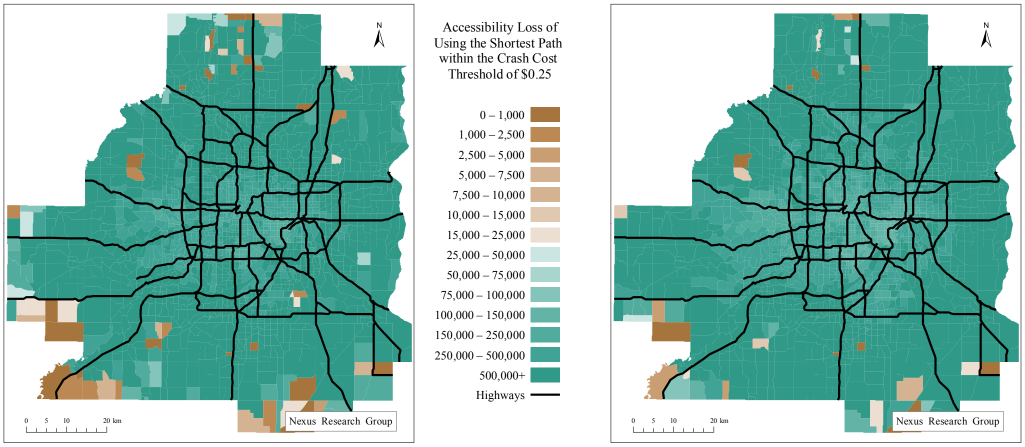
(a) $0.05

(b) $0.10



(c) $0.15

(d) $0.20



(e) $0.25

(f) $0.30

FIGURE 6 : Accessibility Loss of Using the Shortest Travel Time Path Comparing with the Safest Path with different Crash Cost Threshold from $0.05 to $0.30

CONCLUSION

Crash cost, as one of the key cost component of travel, reflects the safety performance of roadways. The safest path was proposed to estimate the minimum crash cost during traveling, which represents the optimal solution of route choices for travelers from the perspective of safety.

This study built a framework of link-based crash cost analysis, analyzed the crash cost for the road network in the Minneapolis - St. Paul metropolitan area, found the safest path for all the OD pairs, and aggregated it to evaluate job accessibility.

Generally, highways are safer than local roads. Highways serve more trips if only the safest path is selected for travelers.

The work trip flows based on the safest path, however, do not coincide with flows based on the shortest travel time path, which reflects a significant difference between those two types of path. For instance, travelers need much more time to travel following the safest path, and generate greater crash costs following the shortest path. Mitigating such a conflict is an efficient way to improve the performance of the network.

Job accessibility based on the safest path shows the similar distribution patterns as that based on the shortest travel time path that TAZs with higher job accessibility center on downtown Minneapolis. Accessibility decreases along with the increase of the distance to the downtown area and the exurban area has the lowest job accessibility. Thresholds have significant effects on job accessibility. A higher threshold could result in a higher job accessibility overall. But using the crash cost threshold makes the accessibility change in a non-smooth way such that a TAZ with a lower accessibility could be surrounded by those with higher ones. The reason is that some unavoidable links, which trips from some TAZs have to pass through, have a relative high crash cost.

Accessibility differences of using the safest path illustrates a higher accessibility loss in downtown Minneapolis when a lower willingness-to-pay for travel time is set. It declines with the increase of time threshold. At the same time, accessibility differences in exurban areas rise. A similar pattern happens for the accessibility differences using the shortest travel time path.

This research focused on the internal (private) crash cost. Further research, at first, should analyze the external crash cost and evaluate the accessibility based on the safest (external) path. Moreover, a full cost analysis of travel, including other key cost components like time, emission, and money, should be considered. We should also measure accessibility from the perspective of alternate cost components and their composite, covering both internal and external cost. The safety accessibility by alternate traffic modes, transit, bicycling, walking, should also be measured.

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